

Micro-/nanoscaled irreversible Otto engine cycle with friction loss and boundary effects and its performance characteristics

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ABSTRACT

An irreversible cycle model of the micro-/nanoscaled Otto engine cycle with internal friction loss is established. The general expressions of the work output and efficiency of the cycle are calculated based on the finite system thermodynamic theory, in which the quantum boundary effect of gas particles as working substance and the mechanical Casimir effect of gas system are considered. It is found that, for a micro-/nanoscaled Otto cycle devices, the work output W and efficiency η of the cycle can be expressed as the functions of the temperature ratio τ of the two heat reservoirs, the volume ratio r_V and the surface area ratio r_A of the two isochoric processes, the dimensionless thermal wavelength λ and other parameters of cycle, while for a macroscaled Otto cycle devices, the work output W_0 and efficiency η_0 of the cycle are independent of the surface area ratio r_A and the dimensionless thermal wavelength λ . Further, the influence of boundary of cycle on the performance characteristics of the micro-/nanoscaled Otto cycle are analyzed in detail by introducing the output ratio W/W_0 and efficiency ratio η/η_0 . The results present the general performance characteristics of a micro-/nanoscaled Otto cycle and may serve as the basis for the design of a realistic Otto cycle device in micro-/nanoscale.

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1. Introduction

It is well known that the performance analysis of traditional thermodynamic cycles using gases as working substance, i.e. heat engine cycle or refrigeration cycle, are based on the classical ideal gas equation of state. This leads to that under reversible thermodynamic condition, the performance characteristics of the cycles only depend critically on the temperature, volume or pressure of gas system. While the real thermodynamic cycles based on the classical thermodynamic theory not only involve the control parameters but also other performance parameters, i.e. the degree of internal irreversibility, heat leak and so on. Consider the various internal and external irreversibilities of the practical cycle, many useful thermodynamic cycle models, i.e. endoreversible and irreversible cycles are established and used for leading to designing the realistic thermodynamic devices [1–10]. In spite of the fact, most of the studies about the performance of the gas cycle always neglect the influence of boundary of cycle. That is, the classical thermodynamic cycle models and corresponding results only deal with the macroscaled gas systems, in which the boundary effects are unimportant.

Recently, miniaturization of mechanical devices to nanometer length scales [11,12] greatly enhances the consideration of the boundary effect on the system, such as Casimir boundary effect of system [13–15] and quantum boundary effect of gas particles [16–20]. In particular, both the two boundary effects have been used for designing some mechanical power devices [21–24] or thermosize gas cycle system [25,26]. In addition, the influences of boundary on the classical gas cycle are also an important issue. In the literatures [27,28], it has been found that the quantum boundary effect of gas particles confined in finite domain may cause differentiation of behaviors of the gas cycles. In general, for a micro-/nanoscaled gas cycle system, the previous reversible or irreversible cycle models in macro scale and corresponding performance results can not predict its performance characteristics due to the various boundary effects of the system. Further, under reversible and irreversible conditions, the boundary effects on gas system may be different.

In this paper, we established an irreversible cycle model of the micro-/nanoscaled Otto engine cycle with friction loss and different boundary effects, i.e. Casimir boundary effect and quantum boundary effect. The work output and efficiency of the cycle are derived based on the thermodynamic properties of a gas confined in a finite domain [16,17]. The influence of the boundary of cycle on the performance characteristics of the micro-/nanoscaled Otto

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engine cycle is examined under the reversible and irreversible conditions by considering some special examples.

2. Micro-/nanoscaled irreversible Otto engine cycle

2.1. Cycle model

Let us consider an irreversible Otto engine cycle in micro-/nanoscale composed of two isochoric and two adiabatic processes. The temperature-entropy of the cycle is shown in Fig. 1, where the cycle 1–2i–3–4i–1 is the reversible one, while 1–2–3–4–1 is the irreversible one that takes into account the internal irreversibility of the practical cycle. We represented the internal temperatures of the working substance in the points of state s as T_s , where $s = 1, 2, 2i, 3, 4i$ or 4, the volumes of the gas system in the two isochoric processes as V_H and V_L , and the surface areas of the gas system in the two isochoric processes as A_H and A_L . In addition, Q_{41} and Q_{23} are the amounts of heat exchange between the working substance and the heat reservoirs at temperatures T_H and T_L during the two irreversible isochoric processes, respectively. They are always defined positive in the whole paper. Noted that the highest and lowest temperatures of the working substance in the cycle are $T_H(T_H = T_1)$ and $T_L(T_L = T_3)$, respectively.

In the irreversible Otto cycle consisting of states 1–2–3–4–1, the main irreversibility of the system considered here comes from the internal friction loss in the adiabatic expansion process 1–2 and compression process 3–4. It should be pointed out that the irreversibility exists also in the two isochoric processes where the dissipative actions of gas produce entropy leading to modified temperatures of working substance in respect to the reversible cycle isochoric processes 2i–3 and 4i–1. In the present paper, in order to present the main irreversibility characteristics of the cycle system, we introduced the constant expansion and compression efficiencies for the reversible adiabatic expansion process 1–2i and compression process 3–4i as [9,10]

$$\eta_e = \frac{T_H - T_{2i}}{T_H - T_2} \quad \text{and} \quad \eta_c = \frac{T_4 - T_L}{T_{4i} - T_L} \quad (1)$$

Obviously when $\eta_e = 1$ and $\eta_c = 1$, the cycle is reversible.

In particular, for the present micro-/nanoscaled Otto cycle, the thermodynamic properties of gas as working substance will be different from classical one due to the quantum boundary effect of gas particles confined in finite domain [16,17]. This means that the heat exchanges between gas systems and surrounding in the cycle processes may be predicted no more by the classical one and dependent of the boundary of system. It is necessary to calculate in detail the heat exchanges and further derive the work output and

efficiency of the micro-/nanoscaled irreversible Otto engine cycle from the finite system thermodynamic theory. In Refs. [16,17], Sisman and co-worker have been derived the thermodynamic state functions of a gas confined in finite domain, based on Maxwell–Boltzmann statistics. For instance, the free energy of an ideal gas confined in finite domain is given by

$$F = -Nk_b T \left[\ln \left(\frac{V \pi^{3/2}}{8NL_c^3(T)} \right) + 1 \right] + \frac{AL_c(T)}{2V\sqrt{\pi}} Nk_b T \quad (2)$$

where $L_c(T) = h/\sqrt{8mk_b T}$ is one half of the most probable de Broglie's wave length of the particles at temperature T , h is Planck's constant, m is the atomic mass and k_b is Boltzmann's constant. N is the total number of particles in the whole confinement volume, A is the surface area of the domain and V is the volume of the domain.

It is clearly seen from Eq. (2) that the thermodynamic state function of an ideal gas confined in finite domain depends on not only two intensive variables, like temperature and density, but also the boundary, i.e. size and shape of domain. It is interesting that the addition control variables make the gas confined in finite domain cannot fill all the space of the domain and the density goes to zero within the layer approached by the boundary of domain [17,18]. Then, a finite scaled, i.e. micro-/nanoscaled gas cycle system will be closed no more and the mechanical friction between the piston and cylinder for the cycle can be decreased largely. Furthermore, it will be observed that the quantum boundary effect of gas system gives rise to the differentiation of behaviors of the classical Otto gas cycle.

It is also noted that for a micro-/nanoscaled cycle, another boundary effect, i.e. mechanical Casimir effect of the system should be considered [13,14,29,30]. That is, in the adiabatic expansion process 1–2, the input of mechanical power is required against the Casimir force, while in the adiabatic compression process 3–4, the mechanical Casimir energy is released via the Casimir force [29]. Then, the present four-step closed cycle consisting of four mechanical steps should involve the gas heat energy or work and the mechanical Casimir energy. However, in the adiabatic expansion and compression processes, the released Casimir energy and the input of mechanical power are equal and the net Casimir energy change around the cycle is zero since the Casimir energy is a state function [30]. Therefore, the Casimir effect does not affect the operation of the micro-/nanoscaled irreversible Otto cycle and its performance characteristics, despite the complicity of the Casimir effect in micro-/nano cavity system.

2.2. Work output and efficiency

In following paper, in order to obtain the expressions for the work output and efficiency of the cycle, we first calculate heat capacity C_V at constant volume and the entropy of an ideal gas confined in finite domain. Using Eq. (2), one can derive the internal energy and entropy of an ideal gas confined in micro-/nanoscaled system as

$$E = \frac{3}{2} Nk_b T + \frac{AL_c(T)}{4V\sqrt{\pi}} Nk_b T \quad (3)$$

and

$$S = Nk_b \left[\ln \left(C \frac{V(1 - AL_c(T)/4V\sqrt{\pi}) T^{3/2}}{N} \right) + \frac{5}{2} \right] \quad (4)$$

where $C = (2\pi mk_b)^{3/2}/h^3$. In Eq. (4), the approximation $\ln(1 - x) \cong -x$ for $x \ll 1$ has been used since $AL_c(T)/4V\sqrt{\pi} \ll 1$ for a micro-/nanoscaled system. Further, from Eq. (3), one obtains the heat capacity at constant volume

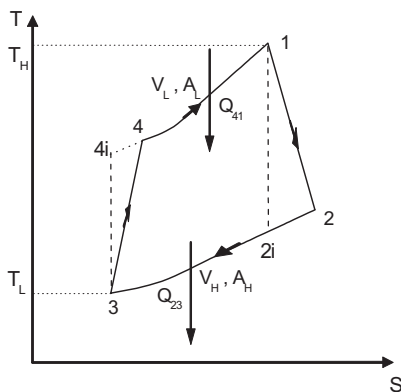


Fig. 1. Entropy-temperature diagram of a micro-/nanoscaled irreversible Otto cycle.

$$C_V = \left(\frac{\partial E}{\partial T} \right)_V = \frac{3}{2} Nk_b + \frac{AL_c(T)}{8V\sqrt{\pi}} Nk_b \quad (5)$$

Then, by making use of Eq. (5) the amounts of heat exchange $Q_{23} = \int_2^3 C_V(T, A, V) dT$ in one isochoric process 2–3 of the micro-/nanoscaled Otto cycle can be calculated as

$$Q_{23} = \frac{3Nk_b}{2} (T_2 - T_L) + \frac{Nk_b A_H}{4V_H\sqrt{\pi}} [T_2 L_c(T_2) - T_L L_c(T_L)] \quad (6)$$

and the amounts of heat exchange $Q_{41} = \int_4^1 C_V(T, A, V) dT$ in the other isochoric process 4–1 can be expressed as

$$Q_{41} = \frac{3Nk_b}{2} (T_H - T_4) + \frac{Nk_b A_L}{4V_L\sqrt{\pi}} [T_H L_c(T_H) - T_4 L_c(T_4)] \quad (7)$$

In addition, using Eq. (4), the adiabatic equations in the two isentropic adiabatic processes 1–2i and 3–4i can be obtained as

$$V_L \left(1 - \frac{A_L}{V_L} \frac{L_c(T_H)}{4\sqrt{\pi}} \right) T_H^{3/2} = V_H \left(1 - \frac{A_H}{V_H} \frac{L_c(T_{2i})}{4\sqrt{\pi}} \right) T_{2i}^{3/2} \quad (8)$$

and

$$V_H \left(1 - \frac{A_H}{V_H} \frac{L_c(T_L)}{4\sqrt{\pi}} \right) T_L^{3/2} = V_L \left(1 - \frac{A_L}{V_L} \frac{L_c(T_{4i})}{4\sqrt{\pi}} \right) T_{4i}^{3/2} \quad (9)$$

respectively.

For convenience of analysis, let us introduce the dimensionless thermal wavelength

$$\lambda = \frac{A_L}{V_L} \frac{L_c(T_L)}{4\sqrt{\pi}}$$

the temperature ratio $\tau = T_L/T_H$ of the two heat reservoirs, the volume ratio $r_V = V_H/V_L$ and the surface area ratio $r_A = A_H/A_L$ of the two isochoric processes. We can solve analytically the Eqs. (8) and (9) and obtain the temperature T_{2i} and T_{4i} .

$$T_{2i} = \left[r_V^{-1} r_A \lambda \sqrt{\tau} + r_V^{-2} r_A^2 \lambda^2 \tau (Z_1/2)^{-1/3} + (Z_1/2)^{1/3} \right]^2 T_H/9 \quad (10)$$

and

$$T_{4i} = \left[\lambda + \lambda^2 (Z_2/2)^{-1/3} + (Z_2/2)^{1/3} \right]^2 \tau T_H/9 \quad (11)$$

respectively, where

$$Z_1 = 2r_V^{-3} r_A^3 \lambda^3 \tau \sqrt{\tau} + 27a_1 + 3\sqrt{3a_1 (4r_V^{-3} r_A^3 \lambda^3 \tau \sqrt{\tau} + 27a_1)},$$

$$a_1 = r_V^{-1} (1 - \lambda \sqrt{\tau}),$$

$$Z_2 = 2\lambda^3 + 27a_2 + 3\sqrt{3a_2 (4\lambda^3 + 27a_2)}$$

and

$$a_2 = r_V - r_A \lambda$$

Using Eqs. (1), (6), (7), (10) and (11), the amounts of heat exchange Q_{23} and Q_{41} become

$$Q_{23} = Nk_b T_H \left\{ \frac{3}{2} \left[1 - \tau - \eta_e \left(1 - \frac{T_1^*}{9} \right) \right] + \frac{r_A \lambda \sqrt{\tau}}{r_V} \left(\sqrt{1 - \eta_e \left(1 - \frac{T_1^*}{9} \right)} - \sqrt{\tau} \right) \right\} \quad (12)$$

and

$$Q_{41} = Nk_b T_H \left\{ \frac{3}{2} \left[1 - \tau - \frac{1}{\eta_c} \left(\frac{\tau T_2^*}{9} - \tau \right) \right] + \lambda \sqrt{\tau} \left(1 - \sqrt{\tau + \frac{1}{\eta_c} \left(\frac{\tau T_2^*}{9} - \tau \right)} \right) \right\} \quad (13)$$

$$\text{where } T_1^* = \left[r_V^{-1} r_A \lambda \sqrt{\tau} + r_V^{-2} r_A^2 \lambda^2 \tau (Z_1/2)^{-1/3} + (Z_1/2)^{1/3} \right]^2, \\ T_2^* = \left[\lambda + \lambda^2 (Z_2/2)^{-1/3} + (Z_2/2)^{1/3} \right]^2$$

Finally, using Eqs. (12) and (13), we can derive the work output per cycle $W = Q_{41} - Q_{23}$ as

$$W = Nk_b T_H \left\{ \frac{3}{2} \left(\eta_e + \frac{\tau}{\eta_c} \right) - \frac{1}{6} \left(T_1^* - \frac{\tau T_2^*}{\eta_c} \right) - \lambda \sqrt{\tau} \left(1 - \frac{r_A \sqrt{\tau}}{r_V} \right) - \lambda \sqrt{\tau} \left[\sqrt{\tau + \frac{1}{\eta_c} \left(\frac{\tau T_2^*}{9} - \tau \right)} + \frac{r_A}{r_V} \sqrt{1 - \eta_e \left(1 - \frac{T_1^*}{9} \right)} \right] \right\} \quad (14)$$

and the efficiency $\eta = W/Q_{41}$ as

$$\eta = 1 - \frac{9(1 - \tau - \eta_e) + T_1^* + 6r_A r_V^{-1} \lambda \sqrt{\tau} \left(\sqrt{1 - \eta_e \left(1 - T_1^*/9 \right)} - \sqrt{\tau} \right)}{9(1 - \tau + \tau \eta_c^{-1}) - \tau T_2^* + 6\lambda \sqrt{\tau} \left(1 - \sqrt{\tau - \tau \eta_c^{-1} + \tau \eta_c^{-1} T_2^*/9} \right)} \quad (15)$$

From Eqs. (14) and (15) we can observe that the work output and efficiency of the irreversible Otto cycle in micro-/nanoscale are the functions of τ , r_V , r_A , λ , η_e , η_c , and other parameters of cycle. Therefore, the performances of the present Otto cycle in micro-/nanoscale depend strongly on the boundary of system, i.e. the surface area of cycle and the dimensionless thermal wavelength. While for a macro-scaled Otto cycle, $\lambda \rightarrow 0$ and the quantum boundary effect can be neglected. Furthermore, as $\eta_e = \eta_c = 1$, Eqs. (14) and (15) give the results of classical reversible thermodynamic condition as

$$W_0 = \frac{3}{2} Nk_b T_H (1 - \tau r_V^{2/3}) (1 - r_V^{-2/3}) \quad (16)$$

and

$$\eta_0 = 1 - r_V^{-2/3} \quad (17)$$

respectively. Eqs. (14) and (15) are the main results of the paper. By using the Eqs. (14)–(17), the boundary effect on the performance characteristics of the irreversible Otto cycle in micro-/nanoscale may be analyzed in detail.

2.3. Performance characteristics

In order to investigate the influence of boundary of cycle on the work output and efficiency of a micro-/nanoscaled Otto cycle, we introduced the work output ratio W/W_0 and the efficiency ratio η/η_0 . In addition, for an Otto cycle in micro-/nanoscale, both the reversible ($\eta_e = \eta_c = 1$) and irreversible ($\eta_e = \eta_c = 0.95$) cycle conditions are considered.

By using Eqs. (14)–(17) we can generate the curves of the work output ratio W/W_0 and the efficiency ratio η/η_0 , varying with the temperature ratio τ at given $\lambda = 0.05$, $r_V = 2.5$ and different surface area ratios of cycle, as shown in Figs. 2 and 3. The curves are selected in the 0.1–0.2 range of τ for a real Otto engine model. We

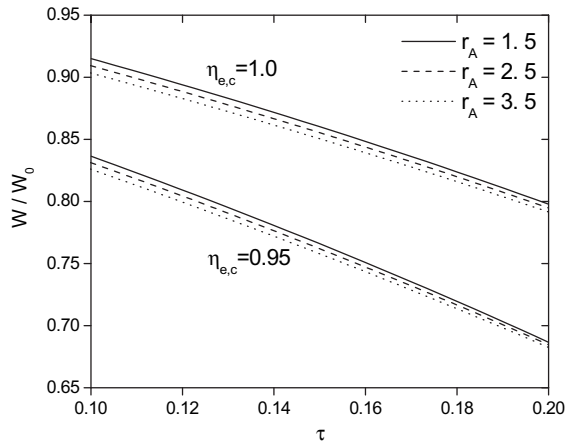


Fig. 2. The work output ratio W/W_0 , vs the temperature ratio curves for different surface area ratios of cycle at given $\lambda = 0.05$, $r_V = 2.5$ under the reversible and irreversible conditions.

can observe from Fig. 2 that the work output ratio W/W_0 decreases monotonically with an increase in τ for different surface area ratios regardless of reversible and irreversible conditions. In particular, even under the reversible conditions, the work output ratio W/W_0 is always less than 1. Thus, the influence of boundary of cycle on the work output of an Otto engine cycle in micro-/nanoscale is disadvantageous. In addition, the work output ratio W/W_0 decreases slightly as r_A increases at a given τ . This means that under the quantum boundary effect condition, one can improve the work output of the cycle by decreasing properly the surface area ratio r_A .

It is obvious from Fig. 3 that the curves of the efficiency ratio η/η_0 varying with the temperature ratio τ for different surface area ratios and these results are interesting to note. For instance, under the reversible condition, the efficiency ratio is almost a constant but always larger than 1 with an increase in τ , as the value r_A is small, i.e. $r_A = 1.5$; while it decreases slightly and is always less than 1 with an increase in τ , as the value r_A become larger, i.e. $r_A = 3.5$. Then, in order to attain the larger efficiency of cycle, the value of surface area ratio r_A should approach to 1. In such cases, the influence of boundary of cycle on the efficiency can be advantageous and cannot be represented by some irreversible parameters. While under the irreversible condition, the efficiency ratio is monotonically decreasing function of τ and always less than the

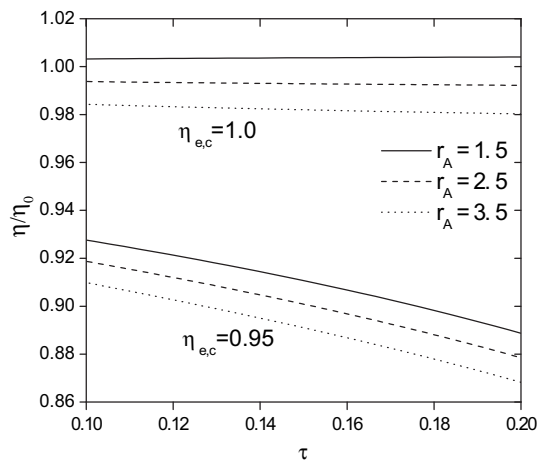


Fig. 3. The efficiency ratio η/η_0 , vs the temperature ratio curves for different surface area ratios of cycle at given $\lambda = 0.05$, $r_V = 2.5$ under the reversible and irreversible conditions.

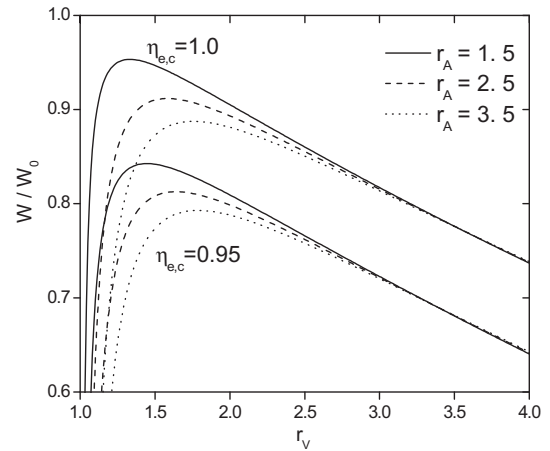


Fig. 4. The work output ratio W/W_0 , vs the volume ratio r_V curves for different surface area ratios of cycle at given $\lambda = 0.05$, $\tau = 0.15$ under the reversible and irreversible conditions.

one of reversible condition. Similarly, the efficiency ratio also decreases with an increase in r_A for a given τ .

Figs. 4 and 5 present the curves of the work output ratio W/W_0 and the efficiency ratio η/η_0 varying with the volume ratio r_V at given $\lambda = 0.05$, $\tau = 0.15$ and different surface area ratios of cycle under the reversible and irreversible conditions. It is observed from Fig. 4 that for the two conditions, the work output ratios W/W_0 are not the monotonous functions of r_V and exist the maximum values at the small values r_V , which can be attained by numerical solution. Further, the maximum values decrease with an increase in r_A at given other parameters. This makes that the work output of cycle may be improved when the surface area ratio approaches to 1. From Fig. 5 we can observe that the efficiency ratio η/η_0 is monotonically increasing function of r_V but monotonically decreasing function of r_A under the reversible condition. Further, the efficiency of the cycle can be larger than classical one when the surface area ratio approaches to 1, while the volume ratio deviates from 1. Under the irreversible condition, the efficiency ratio η/η_0 exists a maximum value but is always less than 1. And the efficiency is also improved when the value r_A approaches to 1. The results discussed above can lead to selecting properly the surface area and volume of system for designing a micro-/nanoscaled Otto engine cycle.

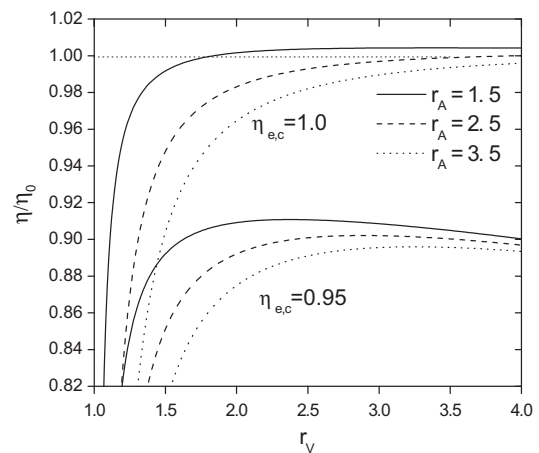


Fig. 5. The efficiency ratio η/η_0 , vs the volume ratio r_V curves for different surface area ratios of cycle at given $\lambda = 0.05$, $\tau = 0.15$ under the reversible and irreversible conditions.

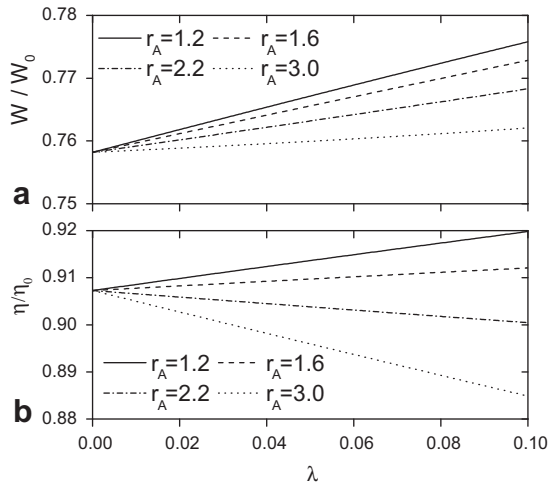


Fig. 6. The work output ratio W/W_0 and the efficiency ratio η/η_0 , vs the dimensionless thermal wavelength λ curves for different surface area ratios of cycle at given $\tau = 0.15$, $r_V = 2.5$, $\eta_e = \eta_c = 0.95$.

We can also generate the curves of the work output ratio W/W_0 and the efficiency ratio η/η_0 , varying with the dimensionless thermal wavelength λ at given $\tau = 0.15$, $r_V = 2.5$, $\eta_e = \eta_c = 0.95$ and different surface area ratios of cycle, as shown in Fig. 6(a) and (b). One can observe that the work output ratio W/W_0 is monotonically increasing function of λ for some different surface area ratios. For the efficiency ratio η/η_0 , it is monotonically increasing function of λ for the small values of the surface area ratio, but monotonically decreasing function of λ as the surface area ratio becomes larger. Thus, in order to attain larger work output and proper cycle efficiency, the dimensionless thermal wavelength λ is also an important optimal parameter except the r_A , r_V and τ .

3. Conclusion

In the paper a thermodynamic model of a micro-/nanoscaled irreversible Otto cycle with friction loss and different boundary effects has been established. The expressions of work output and efficiency of the cycle have been derived from finite system thermodynamic theory. In particular, the influence of boundary of cycle on the performance characteristics of the micro-/nanoscaled Otto cycle under the reversible and irreversible conditions are analyzed in detail by introducing the work output ratio W/W_0 and efficiency ratio η/η_0 . Some important optimal performance parameters of the cycle are determined by the numerical calculation. In principle, these special performance characteristics may be probed experimentally by designing an Otto engine in micro-/nanoscale with nanotechnology. While for a degenerate quantum gas system in micro-/nanoscale, the quantum boundary effects may be more significant. The problem can be analyzed in more detail from the quantum statistics theory [19,20].

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Nomenclature

- A : surface area of the domain (m^2)
 A_{HL} : maximum and minimum surface areas of the gas system (m^2)
 C_V : heat capacity at constant volume (J/K)
 E : internal energy (J)
 F : free energy (J)
 N : total number of particles in the whole confinement volume
 $Q_{23,41}$: amounts of the heat exchange between the working substance and heat reservoirs during the two isochoric processes (J)
 r_A : surface area ratio of the two isochoric processes
 r_V : volume ratio of the two isochoric processes
 S : entropy (J/K)
 T : temperature (K)
 T_{HL} : highest and lowest temperatures of heat reservoirs (K)
 T_s : internal temperature of the working substance in the points of state s (K)
 V : volume of the domain (m^3)
 V_{HL} : maximum and minimum volumes of the gas system (m^3)
 W : work output of the micro-/nanoscaled irreversible Otto engine cycle (J)
 W_0 : work output of classical reversible Otto cycle (J)
Greek symbols
 η : efficiency of the micro-/nanoscaled irreversible Otto engine cycle
 η_0 : efficiency of classical reversible Otto cycle
 $\eta_{e,c}$: constant expansion and compression efficiencies
 λ : dimensionless thermal wavelength
 τ : temperature ratio of the two heat reservoirs